Impacts of wind-evaporation feedback in outer regions on tropical cyclone development

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要約

It is important to understand the intensification processes of tropical cyclones (TCs) for pursuing predictability of TCs and assessment of their impacts. Unfortunately, the large amount of uncertainty remains in the recent operational forecasting systems, especially due to the rapid intensification (RI). The RI is considered to be a self-amplifying intensification process (i.e., positive feedback). It is well known that the dominant factor in the development of TCs is diabatic heating by water vapor condensation in the eyewall, and the water vapor source is evaporation from the sea surface. Since the amount of sea surface evaporation is assumed to be dependent on the surface wind speed, it is crucial to clarify the process of the feedback between the surface wind speed and evaporation from the sea (i.e., wind-evaporation feedback).

In Chapter 2, we revisit some persuasive theories of the TC intensification to address their drawbacks, and the concept of the conventional feedback processes: the conditional instability of the second kind (CISK), cooperative intensification theory, and the wind-induced surface heat exchange (WISHE). It has been widely considered that TCs are able to develop quickly with the positive feedback between the TC wind and local evaporation such as WISHE. However, in recent years, observational and numerical studies have pointed out that the contribution of local evaporation may be overestimated. These results also show that the primary water vapor source is inward water vapor flux from the outside of TCs. For this reason, there is no unified theory to resolve the conflicts between them. The second section describes the bulk method of the sea surface water vapor flux which is assumed to be a function of the surface wind speed and water vapor difference at the air-sea interface. We show the concerns for the wind-evaporation feedback focused on local evaporation. The third section the surface friction which induces convergence near the surface.

In Chapter 3, we examine the roles of water vapor flux across the air-sea interface in the outside TC (i.e., light wind region) on the TC development. Using the three-dimensional cloud-resolving nonhydrostatic atmospheric model (JMA-NHM), we perform four idealized experiments in which a TC-like vortex is given to a horizontally uniform environment field. In order to remove the wind speed dependence on the surface water vapor flux outside of the TC, we introduce the lower limits of the 10-m wind speed in calculation of water vapor flux (5, 10, and 15 m s^{-1}). Results show that increasing the lower limit reduces the radial water vapor contrast in the lower troposphere (below 100 m) and suppresses the TC size and intensity at the mature stage by 30%–33% and 5%–14%, respectively, compared to the control run. The increased evaporation enhances the outer convective activity and reduces the radial pressure gradient in the lower troposphere. Consequently, the secondary circulation becomes weak and narrow because the inflow flux is blocked by the convections outside the TC. Moreover, the outer region convection suppresses the rainband activity, within a radius of 300 km from the TC center. It is assumed that the wind-evaporation feedback plays a crucial role in sustaining the secondary circulation and promotes the spin-up.

In Chapter 4, we investigate the wind-evaporation feedback in the outside TC from a case study for TC Hagibis in 2019 because the hypothesis suggested in Chapter 3 have some concerns that the idealized environment ignores various factors such as a vertical shear, steering flow, and non-uniform

thermodynamic field. In addition, there is no proof that whether the initial vortex is consistent with the realistic structure of a TC. We pick up TC Hagibis (2019) because of its high intensification rate (100 kt day^{-1}, according to the Joint Typhoon Warning Center). Similar to the experimental design in Chapter 3, we apply a lower limit into the bulk formula to cut off the wind-evaporation feedback outside Hagibis (2019). We perform two sensitivity experiments using the same model in Chapter 3, JMA-NHM: the control run with no limits (CTL), and disabled feedback run with a lower limit of 10 m s^{-1} (MIN10). The derived results show some inconsistencies with the findings in Chapter 3. The intensity in the CTL run was smaller than that in the MIN10 run, and its RI onset was 6 hours behind the MIN10's onset. Besides, the intensification rate in MIN10 is larger than that in CTL. The analysis of water vapor budget in the inner core of the simulated TC reveals that the dominant source of water vapor for the TC development is the horizontal inward moisture flux. The contribution of the sea surface moisture flux is less than 5% of the horizontal inward flux after the onset of intensification. In MIN10, the water vapor convergence becomes large earlier, resulting in the stronger intensity of the simulated TC. Considering that there is the wide and robust inflow layer to TC Hagibis (2019) at the initial condition, it is simulated that the TC early gathers the large amount of water vapor from the excessive evaporation at the sea surface with the weak wind. Thus, it is the reasons why the MIN10 experiment performed the stronger TC without the wind evaporation.

In summary, the present thesis points out that the radial contrast of water vapor near the surface is important for the TC organization than the amount of water vapor itself. The radial contrast of water vapor field is more crucial than the CISK paradigm. In addition, the dominant role of the horizontal moisture flux suggests that it is insufficient to diagnose the maximum potential intensity (MPI) of TCs based on the WISHE paradigm which consists of only eyewall (and outflow layer) information. Based on the idealized experiments, we propose the new hypothesis of the wind-evaporation feedback. Our findings give a very different interpretation of the wind-evaporation feedback on the TC development from the conventional ideas.

Lastly, we have to mention some issues for further progress. First of all, the concern is the inconsistency of the results from the idealized simulation (Chapter 3) and real case simulation (Chapter 4). In the real case experiments, the sea surface evaporation outside the TC results in earlier intensification. Since the reason is considered to be the initial conditions or the case dependency, it is insufficient to prove our hypothesis from the single case study. To verify the general roles of suppressing sea surface evaporation outside TCs, it is necessary to use the statistical approach. Next, in relation to the above, it is to construct the explanatory variable based on the radial contrast of water vapor into the statistical intensity prediction models. These models use atmospheric and/or oceanic parameters to predict the intensity change of TCs. Based on the new wind-evaporation feedback hypothesis, the radial distribution of water vapor (or sea surface latent heat flux) is listed as the candidates of the explanatory variable. Considering that convections outside the TC block the water vapor transport to the TC system, it is favorable for the TC intensification that the atmospheric conditions in the outer regions are convective stable. Thus, the indication of the stability of the atmosphere, such as convective inhibition (CIN) and the distribution of outgoing long-wave radiation (OLR), is also considered to be explanatory variable. We would like to assess the predictability and the contribution of new explanatory variables to the total intensity change. If these issues are cleared, it will bring more improvement in the forecast accuracy.

別　紙

論文審査の結果の要旨

台風の発達理論には，深い対流による潜熱開放に関わる CISK（第 2 種の条件付き不安定）理論と，海面での風と蒸発のフィードバックが重要だとする理論がある。台風の急速な発達は予測が難しく，台風予報上の大きな問題になっている。青野憲史の博士論文は台風発達における外縁部の風・蒸発フィードバックの影響を調べるために，台風外縁の弱風域で蒸発の風速依存性を除去する数値実験を行った。第２章において，背景となるこれまでの台風発達理論と風・蒸発フィードバックの研究を整理している。

第３章では，軸対象の理想的な台風を設定して実験を行った。弱風域の風速に下限を設ける実験により，外縁域で海面蒸発が盛んになると台風は発達しにくくなることを明らかにした。このことは，下層の水蒸気の多寡よりも動径方向の強い水蒸気傾度の方が台風発達に有利であることを意味する。この結果は，これまで考えられてきた発達理論とは異なるフィードバックが存在ことを示している。

第４章では，現実の台風として記録的な急発達をした 2019 年の Hagibis（第 19 号，令和元年東日本台風）を例として，同様の実験を行った。理想的な台風の場合とは異なり，風速依存性がない方が，台風が早く発達した。これは初期状態で外縁部に存在した多量の水蒸気が，効率的に台風内部へ流れ込んだためと考えられる。この結果は，様々な構造を持つ現実の台風に適用できる新たな仮説と，それを検証する数値実験が必要であることを示唆している。

以上の結果は、台風発達理論に新たな展開をもたらすものである。また，初期条件の作成手法や交換係数の精密化などを通して，台風強度予報の改良に重要な示唆を与えるものであり，本人が自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。したがって，青野憲史提出の博士論文は，博士（理学）の学位論文として合格と認める。